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14. ABSTRACT

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Atomization of Wall-Bounded Two-Phase Flows (Preprint)

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Abstract

The current understanding of droplet generation processes from liquid films is reviewed. Films are defined as liquids with one free and one wall-bound surface. In many of the systems where films occur atomization is an undesirable side-effect of the two-phase flow. The motivation for this study, however, is a process where atomization from the film is the goal—a gas-centered swirl coaxial rocket injector. Because atomization is often unwanted in film configurations, few studies focus on the mechanisms that cause atomization. The large body of literature on the atomization of jets and sheets is, therefore, utilized to develop an understanding of film atomization. Similarities and differences between the geometries are discussed as applicable. Generally, the atomization is considered to involve two steps: the creation of a disturbance on the film surface and the breakdown of this disturbance into droplets. Prompt Atomization, where atomization occurs directly at a nozzle exit, is also briefly considered. Several atomization mechanisms are identified and qualitatively described.

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I. Introduction

The physical processes that lead to the disintegration of a liquid or the formation of droplets from its surface are termed atomization mechanisms. The breakup of jets, sheets and films occurs due to the complex interaction of several forces: aerodynamic, viscous, surface tension and inertial, for example [1-3]. The absolute and relative values of these forces and their evolution determine the mechanisms involved in atomization. Knowledge of the mechanisms allows the development of a quantitative description of the atomization—droplet size, distribution and velocity, for example. In reality, however, uncertainty about the exact mechanisms involved remains; even if the processes are understood, they are often too complex to fully describe in a quantitative way. Nevertheless, a knowledge of the operable atomization mechanism(s) is important as it leads to the definition of specific atomization regimes, implies qualitative aspects of the resulting spray and suggests relevant scaling laws. Scaling laws are particularly important in some atomization applications, such as rocket engines and powdered metal production, where full-scale tests at operational pressures and/or temperatures can be costly and make measurements difficult. A solid understanding of the physics involved in the breakup process, therefore, helps to focus experiments and ground correlations as well as directing the development of new atomizer concepts.

Here atomizers are broadly classified into one of three groups: jet, sheet or film. In jet atomization the liquid is introduced as a cylindrical stream (Fig. 2a). Sheet atomization is characterized by a stream of liquid that has two free surfaces (Fig. 2b). A film is similar to a sheet, but is bounded on one side by a wall. Films may have several geometries, but the most common in atomization processes are flat or annular (Fig. 2c). Note that this nomenclature differs somewhat from that commonly used in the literature, where sheet, film and jet may be used interchangeably [4, 5]. To avoid confusion and clarify the following discussions, however, the above definitions will be used throughout this paper: a sheet has two free surfaces while a film has one wall-bounded and one free surface; a jet has only one surface, and it is a free surface. Atomization mechanisms vary somewhat between the three different geometries because the relative importance of individual forces differs for each configuration [3, 6]. However, similarities are found between the groups [5, 6]. Vastly different operating conditions and diverse figures of merit are used for the range of applications in which film atomization occurs; this diversity limits the applicability of empirical correlations. For these reasons atomization mechanisms have been stressed over correlations.

The motivation of this work is the recent studies of a rocket injector where atomization occurs from an annular film (see Fig. 1) [7, 8]. The main focus of this review paper, then, is potential atomization mechanisms of films in parallel flows. Liquid film flows and atomization are found in bow sheets on ships, cooling tubes and towers, water chutes and spillways, a select group of atomizers and elsewhere. The main body of atomizer literature deals with jets or sheets, however, as the majority of atomizers utilize these configurations. Comparatively little research exists on atomization mechanisms in the film configuration. Consequently, the summary of film atomization mechanisms will be predicated on brief reviews of the basic atomization regimes of jets and sheets. The similarities and differences between the geometries will be emphasized.

Section II covers the atomization regimes of the three geometries along with a brief discussion of atomizers that do not easily fit into these three main categories, e.g. effervescent atomizers. The review of regimes will be used set the stage for the subsequent discussion of specific atomization mechanisms and submechanisms.

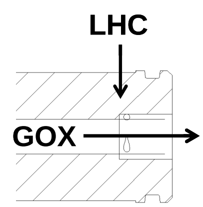

Figure 1: Gas-centered swirl coaxial injector where atomization occurs from a film

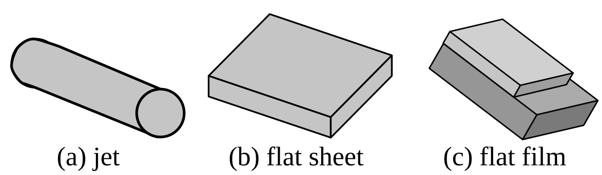

Figure 2: Potential configurations for atomization liquid

II. Atomization Regimes

A. Jets

This section presents a much abbreviated look at the atomization regimes of jets with an eye towards possible mechanisms in film atomization. For a more thorough review of jet atomization the reader is referred to the influential book by Lefebvre [2] or the review articles of Lasheras and Hopfinger [9] (jets in coflow), Margason [10] (jets in cross-flow) and Sallam, Dai and Faeth [11] (turbulent jets). As part of the abridgement of this subject, jets in cross-flow will not be addressed—this configuration is unlikely in film atomiza-

tion and is, therefore, not considered to further the agenda of this paper.

Experimental findings suggest three main regimes for jet atomization: Rayleigh mode, Surface Breakup (Taylor mode) and Prompt Atomization [9, 12, 13]. In the Rayleigh mode hydrodynamic instabilities produced by surface tension cause the jet surface to undulate [13]. Eventually the instabilities become large and the liquid column narrows to the point that a droplet is formed. These surface-tension-driven instabilities may be augmented by aerodynamic effects or liquid turbulence. In sheets and films surface tension is generally not destabilizing; but a similar atomization mechanism exists in the sheet geometry. The Surface Breakup regime is characterized by disturbances (waves, ligaments) on the surface of the jet. These disturbances may be caused by liquid turbulence [14], hydrodynamic instabilities [13] or the interaction of vortices in the gas phase [15]. Various mechanisms cause these protuberances to become droplets. Finally, in the Prompt Atomization regime disintegration starts at the nozzle exit [12].

In addition to these three main regimes for jet atomization, the turbulent jet work of Sallam et al. [11] found three turbulent jet regimes: a weakly-turbulent Rayleigh-Like mode, a Surface Breakup (primary-column breakup) mode and an Aerodynamic Bag/Shear Breakup mode. In the Rayleigh-Like mode instabilities are enhanced by the turbulence, but the behavior is basically identical to the Rayleigh mode [11]. Again, this is mainly a surface-tension driven instability phenomenon. In the Surface Breakup mode, the main mode of turbulent breakup, turbulence causes surface protrusions; this mode is directly related to modes seen in sheet and film atomization and will be discussed in depth in the Atomization Mechanisms section. The Aerodynamic Bag/Shear Breakup mode is characterized by whole jet oscillations and large departures from the mean flow direction; consequently, breakup is accomplished by mechanisms similar to those of a jet in cross-flow [11]. Clearly, a film could not oscillate as a whole, so this mode is not discussed further. (Again, Margason [10] presents a good review of jets in cross-flow.)

B. Sheets

The breakup of liquid jets and sheets differ in various fundamental ways. Most notably, surface tension is a stabilizing force for the vast majority of sheets [6]. Aerodynamic forces are of great importance in nearly all sheet breakup processes while they are secondary in the Rayleigh breakup regime of jets. Despite these differences, liquid-turbulence-induced breakup mechanisms have been shown to be similar [16, 17], clearly indicating the ability to compare the two. While jets and sheets differ in superficial visual similarity, sheets and films clearly resemble each other. Consequently, a greater degree of similarity is expected between sheets and films than between either and jets. This section on atomization regimes in sheets is still abbreviated, but it is more detailed than the jet section because more similarities with films are expected. The reader is directed elsewhere for a more in-depth review, e.g. Lefebvre's [2] book on atomization or the paper by Sirignano and Mehring [18]. Again, nonparallel (impinging) flows will not be considered here.

A review of the literature suggests that sheet atomization can be broken down into four general regimes [16, 19-22]. Rarely are all four discussed within the same reference, however. The existing nomenclature for the regimes can be inconsistent across the literature. A unique classification of regimes will be used here which is substantially more general and more related to the underlying atomization mechanisms than earlier classifications. The four regimes are Sheet Pinching, Surface Breakup, Perforated and Prompt Atomization regimes. In the Sheet Pinching regime a long ligament is formed along the entire width/diameter of the leading edge of the sheet. This regime is analogous to the Rayleigh mode in jets—hydrodynamic instabilities cause the surface of the liquid to develop waves which eventually cause a part of the liquid to separate from the bulk. The Surface Breakup mode is characterized by the shedding of droplets from protuberances on the surface of the sheet and is, therefore, similar to the same-named regime in jet atomization. While surface disturbances and sheet pinching may occur simultaneously and involve similar initiating mechanisms, they may also occur independently and are generally dealt with separately in the literature ([21], for example); consequently, they are considered to merit a separation into two different regimes here. If characteristic holes appear and induce breakup then the sheet is in the Perforated regime. Finally, the Prompt Atomization regime is much like the regime of that name in jet breakup—disintegration of the sheet occurs at the exit of the nozzle [3, 21].

A more thorough look at the first regime seems warranted due, in part, to its prevalence in the literature. Sheet Pinching is characterized by the formation of a large ligament from the entire spanwise edge of the sheet. These ligaments are either torn off the end of the sheet (due to aerodynamic forces) or form when the two planes of the sheet come together along a spanwise line due to surface instabilities [4, 19, 23-25]. The large ligaments then break into smaller droplets via Rayleigh breakup ([19], for example); this secondary Rayleigh breakup would not exist in liquid films, as pinching will create a ligament which is attached to the wall. This wall-bounded ligament could, however, undergo other breakup mechanisms. The Sheet Pinching regime has garnered the most attention in the sheet atomization

literature and is implemented in numerous numerical calculations ([4, 19, 26], for example). Adzic et al. [21] also report a gas-pressure-driven mechanism which causes large sections of the sheet to separate. These large sections undergo breakup due to aerodynamic as well as surface-tension instabilities.

The Surface Breakup regime is dominated by the shedding of droplets from disturbances on the surface of the sheet. For the purposes of this paper, the Surface Breakup regime encompasses the rim shedding regime mentioned by Chigier [3]; in other words, disturbances may not exist throughout the entire sheet but only in one section such as near the exit [16, 17] or at the edges of the sheet [3, 27]. Stapper et al. [27] observation at both the limits of their "cellular regime" and in their "stretched streamwise ligament breakup" regime also fall in the Surface Breakup regime. The main body of their "celluar regime" falls into the Perforated regime. At their lower liquid velocity limit atomization occurs from streamwise ligaments originated from a coherent sheet; at higher liquid velocities perforation appear and the sheet moves into the Perforated regime. At even higher liquid and gas velocities the coherent sheet transitions to a series of ligaments at its downstream edge without any intermediate perforations [27].

C. Other Configurations

Not all configurations fit neatly into the main groupings of jet, sheet and film. Impinging jets and effervescent atomizers are two commonly encountered configurations that deny easy geometric classification. In impinging jets, the setup is initially a liquid jet but the collision of two (or more) jets forms a sheet and the subsequent breakup is from this sheet. At the exit plane of an effervescent atomizer the flow can resemble either a jet or a sheet depending on the gas-to-liquid ratio, i.e. the ratio of mass flow rate of the gas to the liquid.

Four atomization regimes for impinging jets are reported in the literature [28, 29]. All of these regimes can be related, in some way, to regimes discussed earlier. At low jet velocities the collision initially forms a sheet but this sheet subsequently collapses into a jet [29]. So any subsequent atomization falls into one of the regimes for jets. At higher jet velocities atomization occurs in the sheet geometry, particularly falling into the Surface Breakup or Sheet Pinching regimes. Waves on sheets formed by impinging jets may be generated from the impact of the jets and then amplified by aerodynamic effects [28] or caused by hydrodynamic instabilities. The last regime, catastrophic breakup, at the highest jet velocities tested, is considered to be the fully developed regime; in this regime periodic waves of droplets are shed from the point of impingement and no sheet is evident [28, 29]. In terms of impinging jets, this regime is an atomization regime: droplets are formed at the earliest time possible; earlier atomization would take place from the jets before they collided. While impinging jets are not directly applicable to the film configuration, they are similar to the situation where a jet of liquid impacts a solid surface. The driving force unique to this configuration, impact waves, may therefore be important in some film atomization problems. Again, the above description is a drastic abridgement of this subject; for further reading the review article of Anderson et al. [29] is recommended.

In effervescent atomizers gas is injected into the liquid at a low relative velocity in order to form a bubbly two-phase flow [30]. This two-phase flow has a much lower sound speed than either the gas or liquid alone, thus the nozzle chokes at much lower speeds. Due to choking in the nozzle, there is a large pressure drop at the nozzle exit. The atomization in effervescent atomizers is related to this pressure drop [30]. Depending on the gas-to-liquid flow rate the flow in the nozzle may be bubbly, slug or annular. On exiting the nozzle, the air (either the bubbles, slug or the inner column) experiences a sudden pressure drop causing it to expand rapidly [30]. This rapid expansion causes bubbles and slugs to shatter the surrounding liquid forming droplets; the annular liquid is fragmented into ligaments by this expansion [30]. These ligaments remain attached to the bulk of fluid remaining in the nozzle. Effervescent atomization will not be considered in the film regime here as the authors found no literature on this configuration; however, similar behavior could be expected with bubbles and slugs inside films undergoing rapid pressure drops—trapped air exploding the liquid in all directions except the wall-bounded one and forming attached and unattached ligaments. For further review of effervescent atomization the reader is referred to the review article by Sovani et al. [30].

D. Films

Much of the literature regarding film flow is focused on water waves in oceans or spillways, where atomization is not the main focus. Another large body of literature exists on heat-exchanger pipes where the focus is predicting film depths and/or heat transfer; these works are often concerned about atomization but research is centered on the entrainment rate of the liquid, not on the mechanisms by which the liquid becomes entrained. The literature that does address atomization mechanisms considers only a Surface Breakup mode where disturbances on the film surface evolve into droplets ([31-33], for example). As discussed earlier, however, there is the possibility for regime similar to Sheet Pinching and the Rayleigh mode where an entire downstream section of fluid separates. Perforations, though unlikely to be important factors in most rocket injectors, are also possible under some conditions [34]. The breakup of a wall-bounded

ligament, or ribbon, could differ substantially from the breakup of the entire film and warrants future investigation. Because pinching is a misnomer in the film flow geometry and the breakup is not due to surface tension this regime deserves a new moniker; it will be titled Ribbon Forming in subsequent discussions. A third potential regime is a Prompt Atomization regime which may exist if the liquid is initially sheltered. Only flows that are, in the mean, parallel are considered here. Reasons for this abridgement include a lack of literature on the subject of impinging air flows and the large amount of information, known and unknown, regarding the parallel configuration. One additional similarity and complexity shared by films and sheets is the existence of multiple configurations, generally flat or annular. In annular flow, swirl may be added which can change the flow evolution; as discussed earlier, however, the addition of swirl may change the growth of instabilities on the surface of the film but has not been found to alter atomization mechanisms [35].

III. Atomization Mechanisms

In the Prompt Atomization regime catastrophic breakup of the liquid occurs over a very short distance. In all other regimes atomization occurs through the creation and, possibly, propagation of a surface disturbance followed by the creation of a droplet or droplets from the disturbance. In many regards only this last action, droplet creation, constitutes atomization. The formation and growth of a disturbance that is later atomized is an important part of the entire process, however. Consequently, this section opens with a discussion of the formation of a disturbance (wave, ligament or perforation). A section outlining the breakdown of this disturbance into a droplet(s) follows. Again, the focus here is on mechanisms found in film atomization. Prompt Atomization mechanisms are discussed following the section on disturbance breakdown. This section closes with the presentation of another mechanism, film separation, which does not easily fit into the earlier section on disturbance formation and breakdown.

A. Disturbance Formation

The disturbances discussed here include waves, ligaments and sheet perforations. The effects of bubbles and droplets interacting with the surface are also discussed. Waves can occur over the entire surface, or they can be localized three-dimensional structures. Ligaments are, generally, liquid projections whose lengths exceed their widths, but this term can also be used to describe any isolated three-dimensional protuberance whose generation is not due to wave dynamics. Perforations are breaks in the sheet or film, holes, which are shaped as a closed circle or oval or as an open parabola-type shape.

<u>Liquid Turbulence</u>

The effects of liquid turbulence on the liquid-gas interface have been studied in depth in all three configurations by Faeth and his coworkers, principally Wu, Dai and Sallam [5, 16, 36] with the findings that (in the Surface Breakup regime) the mechanisms involved did not differ appreciably between the three configurations [5, 17]. The surface mode of turbulent breakup occurs due to the interaction of turbulent eddies with the interface of the liquid [11, 36, 37]. This interaction causes the formation of ligaments. Sarpkaya and Merrill [37] give an in-depth description of eddy dynamics in flat films while Faeth and coworkers present a simplified, quantitative model of ligament formation [36, 38]. Viscous dissipation of the turbulent energy causes smaller and fewer ligaments to be formed as the distance from the liquid-air contact point increases [36, 39].

Liquid turbulence has garnered experimental and theoretical attention in the film configuration specifically. Experimental observations by Dai et al. [5] as well as Sarpkaya and Merrill [37, 39] demonstrate that liquid turbulence leads to the formation of ligaments in film flow geometries. Dai et al. [5] compared turbulent outer annular film atomization with turbulent jet atomization and found the two to be remarkably similar allowing earlier theoretical descriptions for jets to be used to quantitatively describe the formation of ligaments on the film surface.

These works have focused on protuberances formed by liquid turbulence that is fully developed upon the liquid's introduction as a film. Recent work by Lioumbas et al. [40] suggests that the transition from laminar to turbulent flow may be responsible for initiating solitary waves in film flows. They define solitary waves as waves with large amplitudes and relatively long wavelengths. Their findings are for inclined, stratified pipe flows with and without parallel gas flow, but the findings are similar to those for free falling films. The intermittent way in which flow transitions from laminar to turbulent is suggested as a reason for the intermittency of the solitary waves, which are separated by relatively large stretches of smooth, flat film [40].

<u>Hydrodynamic Instabilities</u>

A large body of work on the Rayleigh instability (surface tension driven instability) of jets exists, but, as discussed in the jet regime section, this mechanism does not directly cause breakup in films and will not be detailed here. This mechanism is responsible for breakdown of ligaments, however, and will be further detailed in the section on ligament breakdown. Indeed, due to similarities between sheets and films and the relatively larger body of work on them, this review will

focus on the hydrodynamic instabilities in these two geometries only.

The majority of work on sheet disintegration contains instability analyses. This large body of work helps to highlight the difficulties and complexities of developing accurate descriptions of hydrodynamic instability. Most of the work focuses on temporal instabilities, where the growth rate is considered a function of time. There is, however, a body of literature examining spatial instabilities, where the growth rate is a function of distance; a limited amount of work focuses on each separately ([18], for example). Few studies address the full tempero-spatial stability due to the complexity of the resulting equations [13, 18]; continued debate exists on whether the temporal or spatial viewpoint is more appropriate [3, 13]. Recent numerical studies that suggest the short-term temporal growth is important even for waves which are stable at long times [41-43] further complicating the debate; this line of investigation shows promise because it has predicted specific three dimensional structures, streamwise ligaments [43], that classic instability analyses have had difficulties predicting [44]. Additional questions arise from the common practice of linearizing the instability equations in order to avoid the extreme complexity of the full nonlinear formulations. The linear theories must assume that disturbances are small, but when atomization occurs the disturbances can no longer be considered small [45-47]. Clearly, the subject of hydrodynamic instability and instability growth is a complex and active topic worthy of its own review article; definitive conclusions on wave sizes, causes and growth rates are not yet available for the full range of conditions and geometries at which atomization occurs.

As with sheet breakup, much of the literature of film dynamics describes hydrodynamic instabilities. Theoretical investigations into the aerodynamic instabilities of flat sheets began more than fifty years ago; seminal works in this geometry include those by Squire [46] , York et al. [47], Hagerty and Shea [26], Dombrowski and Johns [23] and Li and Tankin [48] among others. Most of the instability modes of films are the same as those found in sheets, although film instability analysis has its own seminal works ([49-52], for example). Differences due to the movement of only one interface in the film versus two in the sheet play little role in the stability of the film but do effect further breakup of the liquid. Differences in boundary layer profiles between the two geometries are important, however. Analyses of infinitely deep films, jets and sheets have observed that velocity profiles, particularly boundary layer profiles, play an important role in determining the instabilities mode of a system [41, 53]. In particular, gas-phase profiles, which are often neglected, have been found to be important [41, 53]. Unfortunately, exact velocity profiles are often unknown and are difficult to predict or measure. Swirl in the gas and liquid phase of annular film flow is also likely to affect film stability as it does sheet stability [35, 54], but little detailed work exists for the film geometry. For further reading on the subject of instabilities in films the work of Boomkamp and Miesen [55], who examine and classify the causes of instabilities in infinitely deep films, and the notable text of Drazin and Reid [56] are recommended in addition to the seminal works listed above.

Wavelengths can be measured from photographs of the film and then compared to predictions. Lavergne [57] found that the visual frequency of the sheet and the frequency of perturbations in the air speed, as measured by a microphone, were in close agreement and that microphone measurements were more easily made. Exact predictions are complicated by a limited knowledge of the flow parameters in the nozzle and resultant film/sheet/jet; theories may require knowledge of the pressure drop across the nozzle [46], the shear layer thickness [9] or other parameters not easily measured or predicted. Despite these complexities, experimental comparisons in films have been favorable [15, 58, 59]. Generally, hydrodynamic instability analyses predict a most unstable wavelength as the one with the fastest (shortest) growth rate and suggest that the droplet size is proportional to this wavelength [47]. This assumption has been successfully used to aid the development of empirical correlations [58]. However, an additional complication was uncovered in a recent study by Li et al. [60]. Their numerical work showed that different droplet diameters could be generated from the same disturbances, including the same wavelength of the disturbance [60]. These findings suggest that not only wavelength, but other properties of the instability are important, for example amplitude and/or evolution time. This highlights an important point not be overlooked in stability analysis: the existence of an instability does not guarantee that atomization will occur. A time scale is involved for the growth of the instability; other mechanisms may produce atomization before the instability grows sufficiently to cause atomization. Finally, even a thorough description of instability formation and growth is not an atomization mechanism—a description of how the droplets form from these instabilities is also needed.

<u>Vortices in the Gas Phase</u>

Structures in the gas phase have the ability to distort the surface of the liquid phase provided they posses enough energy to overcome the momentum of the liquid or its surface energy [61]. Eddies due to gas turbulence also have indirect effects, such as changing the hydrodynamic instabilities of the system. Compared to liquid turbulence and hydrodynamic instabili-

ties, little atomization literature exists in which direct gas phase interactions with the coherent liquid are considered. Lozano et al. [61] studied this mechanism experimentally in the atomization of sheets; they found gas flow separation and its subsequent vortices, as well as vortices formed at the nozzle, helped force the flapping of the sheet.

When considering the film geometry, the authors were unable to find literature that directly investigated the effects of structures in the gas phase on atomization; there are, however, several investigations of the effects of gas turbulence on the formation and growth of waves, particularly through the introduction of hydrodynamically unstable flow conditions [15, 49, 55, 62]. Hydrodynamic instabilities have been addressed in the preceding section. Jurman and McCready [15] suggest that air turbulence helps cause distortions and waves on the liquid surface without giving a specific mechanism. In the case of gas turbulence, turbulent eddies in the gas may act in ways similar to liquid eddies, contacting the interface and causing deformations if they are sufficiently energetic. These distortions can be further enhanced by the turbulent flow of air over their surface leading to disturbance growth and eventual droplet production [62]. Growth may be additionally enhanced due to the nonparallel orientation of some of the velocity fluctuations [15].

Recent work includes a planned investigation of the effect of vortices created by a backward-facing step on a liquid film [63, 64] The single-phase work observed both stationary and shed vortices [63]. A stationary vortex might essentially constrict the flow of the film passing under it. This constriction would accelerate the flow; additionally, a thicker area of film could be created just upstream or downstream of the vortex due to the constriction. The vortex would also change the gas flow downstream of itself leading to different aerodynamic forces. All of these would affect the subsequent behavior of the film possibly causing disturbances or their growth, but would not directly cause atomization. Vortices could produce more complex film behavior if they are able to substantially distort the film surface. As an example, imagine a liquid entering from the bottom of a backward facing step over which gas is flowing (see Fig. 3). The liquid may be unable to penetrate the gas-phase vortex formed at the step. The gas vortex would then pull the liquid up along its upstream edge causing a wave/ligament to form. The vortex might tear a chunk of this liquid off or it would eventually expose it to the on-coming, noncirculating gas flow which could shear off the wave (see Fig. 3). This mechanism may explain findings from simulations of two-phase film flow of "large perturbations of the gas-liquid interface with a wavelength similar in size to the scale of the large, energy containing eddies" [65]. Numerical results of Li et al. [60] show liquid behavior that appears consistent with such a mechanism, especially their results where the liquid and gas were the same fluid (no surface tension) and recent simulations of gas-centered coaxial-swirl injectors show direct evidence of this mechanism [64].

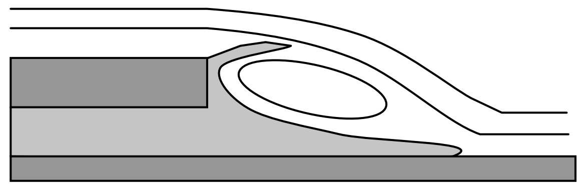

Figure 3. Liquid is "trapped" by a gas-phase vortex. The lines represent streamlines of the flow.

Pressure Fluctuations

Pressure fluctuations can be caused by several processes. Cavitation may drive pressure fluctuations without any interaction from the environment beyond the nozzle; Adzic et al. [21] also reported on a self-contained pressure-driven process for annular sheets. More often, however, pressure fluctuations are caused by changes in the environment outside of the injector, feedback from combustion instabilities, for example. These environmental instabilities may even be driven by the atomization process, creating a feedback loop that is very difficult to model. Pressure fluctuations impact atomization mainly by causing changes to the supply rate of the liquid and gas. Other effects may be present, however, such as the impact waves observed on impinging jets. For brevity discussions of fluctuations not driven by the environment are omitted here despite their potential importance. The reader is referred to refs. [66-68] for discussions of cavitation, Anderson et al. and Jung et al. [28, 29] for discussions of impact waves and Adzic et al. [21] for discussions of their self-contained process

Pressure fluctuations can cause an uneven feed velocity/mass flow for the fuel and/or fluctuations in the gas velocity. If liquid mass-flow changes are large enough they create to a change in film thickness, e.g. a "bulge" following a dip in gas pressure. Experimental studies of annular films have shown that pulses of fluid can lead to atomization in an otherwise nonatomizing film [33]. Additionally, changes in fuel and gas velocity can alter many of the fundamental characteristics of the flow. These changes lead, in turn to differences in hydrodynamic stability behavior, wave growth, aerodynamic shear, etc. When the fuel and gas velocity are affected by pressure changes the growth and breakdown of disturbances should be expected.

"Particle" Interaction

Two types of discrete objects may interact with the gas-liquid interface: droplets and bubbles. Droplets are formed by other atomization mechanisms, but may later

impact the film and contribute to disturbance creation. Bubbles can become trapped in the film by a variety of mechanisms including during droplet collisions or waves breaking. Droplet impingement on walls and films has received a lot of attention in terms of heat transfer and the removal of droplets from the gas, but less in terms of atomization. Bubbles rising to the surface and bursting have been studied for atomization in slow moving films, but not in rocket injector conditions. Indeed, neither mechanism appears to be important for atomization in rocket injectors, the focus driving this paper.

The collision of droplets with a liquid film is an entire subject of its own. Studies centering on atomizing flows are rather limited, with consideration generally given to the impact of a single droplet with a film where the creation of the initial colliding droplet and the behavior of ejected droplets are given little or no consideration. This focus seems justified based on the findings of Woodmansee and Hanratty [69] that splashing is of less importance than other droplet-creation mechanisms. When a droplet collides with a liquid interface it may bounce, merge or create secondary droplets [70]. Secondary droplet creation takes one of three main forms: partial absorption, corona splash or prompt splash [70, 71]. Partial absorption occurs when the droplet initially merges with the film, but a single, wide projection is subsequently createdfrom which a single droplet is ejected [70]. Corona or crown splashing is the type which often appears in photographs. In this type of splashing a thin liquid sheet is created shortly after the droplet impacts the surface. This sheet spreads radially outward and generally develops into fingers which may break into ddroplets due to Rayleigh instabilities [71]. The prompt splash, like prompt atomization, takes place immediately after impact without any observable sheet or jet [71].

Splashing can also occur when liquid projections, such as ligaments, collapse. Studies of ligament collapse during the atomization of turbulent liquid films in quiescent environments found only a few very small droplets were created; additionally, ligament collapse was less common than ligament breakup [37, 72]. Indeed, splashing is unlikely to be an important droplet creation mechanism in atomizers where the goal is the transformation of the entire film to droplets. For splashing to be of primary importance in atomizers a large percentage of the atomized mass would have to come from impacts. Droplets created by splashing impacts will be smaller than the impinging droplet [70, 73], so this condition would require the bulk of the initially created droplets to impact the film. Additionally, atomization through splashing cannot be self-sustaining—eventually droplets will be created that are too small (and/or too slow) to produce new droplets. In situations where atomization is not the primary goal, such as in cooling tubes, splashing may be more important. The overall lower number of droplets and a greater likelihood for secondary droplet dynamics (such as coalescence) may also increase the importance of droplet creation due to splashing.

Gas bubbles can be formed in the film due to the entrainment of air, by the gas coming out of solution or by vapor bubble formation (cavitation or boiling). Lefebvre [2] discusses taking advantage of dissolved gases and/or boiling in a section on effervescent atomization, a term which is now used differently. Chen et al. [74] and Rodríguez et al. [75] discuss gas entrainment due to breaking waves, Rein [72] mentions several other processes that lead to air entrainment such as droplet collision with the film and jet plunging and Woodmansee and Hanratty [69] mention air entrainment due to an interaction of ligaments and waves. These gas bubbles rise through the film and interact with the gas-liquid interface. Droplets and projections are created when the bubbles burst. Two types of droplets can be created [76-78]. They are created by the bursting of the thin film formed between the top of the bubble and the gas. Film droplets are very small, on the order of a few microns [76, 78]. Jet drops form from jets created by the collapse of the bubble cavity. Jet droplets are tens to hundreds of microns in diameter [76, 78]. Not all of the jets created result in the formation of droplets; bubbles must be below a critical size for their collapse to produce a jet that devolves into one or more droplets [77]. Because bubbles produce droplets smaller than themselves and because an intact film must be present to form bubbles, they are likely to be of secondary importance in atomization. Like splashing, however, bubble collapse may be important in situations were the disintegration of the liquid is not the goal.

<u>Perforation Causes</u>

Perforations are a different type of disturbance that leads to atomization. This type of atomization occurs at the upper limit of the “cellular regime” of atomizing sheets described by Stapper et al. [27]. They observe in their experiments that perforations arise due to thinning of the sheet in the streamwise direction as a reaction to streamwise vortices. A limited amount of work exists on this mechanism, but other explanations have been offered as causes for perforations. Fraser [20] observes sheet perforations under certain conditions and suggests that solid particles in the liquid, gas release in the form of bubbles within the sheet, droplet impingement or ripples may cause perforations. Fraser [20] tries various experiments to elucidate the mechanism(s) involved and concludes that bubble release and droplet impingement are unlikely. No concrete information was found supporting any specific mechanism,

although ripples are seen in all cases were perforations form. Hydrodynamic instabilities have also been pegged as a possible cause of sheet perforations [47] and may be responsible for the ripples observed by Fraser [20].

Most of these suggested mechanisms for sheets are possible in the film configuration; however, the authors found no literature dealing with atomization due to film perforations. The growth of holes in quiescent polymer films occupies the bulk of literature on perforated films; in these systems the "droplets" formed are attached to the bounding wall [79, 80]. There is also a large body of literature on the formation of rivulets in vertical and inclined film flows [34, 81, 82]. These systems reveal that the film may "spontaneously" rupture. A closely related mechanism deals with the splitting of a partially-wetting film into ligaments in a rotating centrifugal atomizer [83]; this process is briefly considered in the later discussion of wave splitting.

Film perforations are less catastrophic than sheet perforations because the wetting of the wall creates a surface tension force opposing the growth of the hole, slowing or stopping it. Indeed, perforations may close instead of growing [34, 84] and formed "droplets" may be attached to the wall [85]. Perforations are unlikely to prove important in most film atomization operations until the later stages when the film has thinned substantially. By this point the majority of the atomization properties have been defined by the previous breakup of the bulk of the film. This mechanism may be important, however, if the film is initially quite thin or if the atomized liquid barely wets the nozzle material, e.g., when atomizing polymers or some metals.

B. Disturbance Breakdown

In order for atomization to occur a disturbance must evolve into a droplet. Again, the reader is reminded that the breakdown process requires a finite time and a minimum disturbance height, so that not all disturbed surfaces will undergo atomization. Descriptions of disturbance formation, therefore, are an important part of, but do not fully describe, atomization mechanisms. The following discussion is partitioned based on the type of disturbance creating the droplet(s): wave, ligament or perforation. For the purposes of the following discussion a wave is a protrusion that is generally wide and always wider than it is high; contrarily, a ligament is a protuberance that is generally long and always longer than it is wide. There is some overlap of breakdown mechanisms between these two disturbance types.

<u>Wave Breakdown</u>

Once produced waves may shrink due to energy losses, such as viscous diffustion, or grow due to aerodynamic enhancement, the overtaking of one wave by another or additional wave producing events/drivers. Several wave breakdown possibilities exist: liquid may be stripped from the crests of waves; growing waves may break, like waves on a beach; waves may split to produce a series of ligaments; or waves may cause a long ligament of liquid to be cut-off from its surrounding fluid, i.e. Ribbon Forming. Stripping occurs in both waves and ligaments, but is dealt with in the Ligament Breakdown section below.

The existence of complex three-dimensional gas and/or liquid disruptions can cause single waves or the edge of a sheet to split into multiple waves or ligaments as observed by Stapper et al. [27]. As the wave grows the streamwise disturbances cause thinning in some areas. Eventually these thin areas rupture creating multiple waves/ligaments [27]. Other perforation causes may act locally to produce the same results on a single wave. Rim splitting is essentially caused by these behaviors. Circumstances that lead to perforations and streamwise ligaments in sheets may cause streamwise ligaments to form in films as well. The film may even be split down to the wall producing a series of ribbons. A commonly observed ribbon-forming phenomenon is the splitting of a film as it flows down an inclined or vertical wall. These ribbons are called rivulets. Many theories and correlations have been developed to predict the stability and formation of ribbons on inclined surfaces [34, 81]; the gas and liquid flow rates are generally considered to be very small in these theories. Ribbon formation has also been observed on the surface of rotating cups and disks and a theory exists to calculate their formation [83]. This mechanism remains largely unexplored in atomization literature, despite its possible importance for flows of metal and polymer melts. Individual waves may become ligaments attached to the main flow in other ways. An example is found in the numerical experiments by Li et al. [60]. In this study a hypothetical two-dimensional fluid with no surface tension shows wave growth through the interaction of a vorticity with the surface. While this experiment shows growth along the entire wave, it is possible that local vortices could cause local growth of an area on the wave until its height exceeded its width. Once a wave has evolved to this extent other mechanisms, as discussed in the ligament breakup section below, may cause droplets to be produced.

The formation of a long ligament from a wavy sheet or film occurs in the Sheet Pinching and Ribbon Forming regimes. This mechanism is the most commonly considered one in sheet atomization. The ligament can be formed when a long section of liquid is torn from the sheet [23] or by the (near) meeting of the troughs of waves on each interface (sheets) [4] or, in films, through the meeting of the trough with the wall.

Most works which deal with the atomization of sheets through hydrodynamic instability growth assume this mechanism causes a ligament to form at half wave-lengths [4, 19, 23, 86]: once formed the ligament is assumed to undergo breakup according to Rayleigh's analysis [19, 23]. In films a wall-bounded ligament would be created instead of a free one. Because this ribbon of fluid wets the surface, breakup via the Rayleigh mechanism would not occur. Additional forces due to gas flow over the curved ribbon might change the ribbon's shape or even cause a section of the ribbon to detach from the wall. This segment might then undergo wave breaking, stripping or splitting into ligaments or remain coherent.

Growing waves may reach a size where they are not self-supporting. Wave growth is generally caused by aerodynamic enhancement or wave-wave interaction [74]. Waves that are no longer self-supporting will break, as waves do on a beach. Two main types of breaking waves exist: spilling and plunging. Spilling breakers occur in the small wavelength waves (<2mm) expected in atomizers and are characterized by a capillary-gravity "bulge" on the front-side of the wave which, eventually, leads to turbulence on the down-stream/leeward side of the wave [87]. This turbulence could generate additional disturbances through turbulent-liquid mechanisms. Plunging breakers create a jet which plunges into the film ahead of the wave [87]. This type of breaking is more energetic than spilling and droplets are created from the interaction of the jet with the film, similar in some ways to splashing during droplet impact [74]. Studies of turbulent liquid films [37] have observed droplet formation due to a mechanism similar to jet collapse in plunging breakers [72], but this mechanism creates only a small number of relatively small droplets [74]. Both types of breaking entrain air which may lead to atomization through bubble collapse [72, 74, 87]; still, bubble rupture creates a fine spray and a few larger droplets, so many bubbles would be required to burst before appreciable atomization would occur. An additional indication that wave breaking is of secondary importance is the suggestion by wave stripping theories that few waves would progress to breaking conditions because of mass loss due to stripping.

In a mechanism that, in part, resembles wave breaking [74], the wave may be undercut due to liquid or gas eddies at its base. This undercutting causes the wave to fall in a manner that resembles wave breaking but occurs with less speed and a smaller mass of liquid. Consequently, an open air pocket can be formed between the wave and the surface. The fluid surrounding the pocket generally moves at a greater velocity than the film causing gas to be entrained into the pocket and causing the pocket to grow. Eventually, the air pressure inside this "bag" causes the liquid forming the pocket to catastrophically fail producing small droplets and a thick rim at the pocket's upstream edge. This rim then devolves to droplets via Rayleigh breakup. Azzopardi [33] reports observing this type of breakup in a study of annular, vertically upward film flow. Woodmansee and Hanratty [69] study atomization in a somewhat similar mode. In their experiments they observed a secondary wave accelerating and partially separating from the film to form a thick ligament, a sort of wave splitting. This ligament is stretched and thinned by the air flow until it ruptures. Due to their under-film imaging technique and the relatively thin nature of the bag there is a possibility that the ligaments observed by Woodmansee and Hanratty [69] had attached thin films and that their results indicate bag breakup for flat films as well.

<u>Ligament Breakdown</u>

Numerous mechanisms can cause ligaments to evolve into droplets. These mechanisms include stripping, as briefly mentioned above. Droplets can also be formed by Rayleigh breakup or by liquid turbulence which cuts them off at their base. Another, less explored, possibility parallels the idea of the fragile shattering of droplets as described by Khavkin [88] where viscous droplets subjected to deforming forces behave as solids.

The Rayleigh mechanism for droplet creation from ligaments is the same as that responsible for the breakup of low speed jets. Instabilities driven by surface tension cause the oscillation of the jet surface and, eventually, the creation of a droplet [2]. This mechanism has been observed and described by several investigators studying jet atomization [2, 5, 37, 38]. Rayleigh's theory predicts the creation of droplet 1.89 times the diameter of the jet [2]; experimental observations indicate that droplets created during turbulent liquid film flow are slightly smaller, but on the same order of these predictions [37].

Stripping is one of the most commonly considered type of droplet formation from a film. In this mechanism, the gas strips a mass of liquid from the tip of a wave or ligament once it has reached a particular size [69, 89, 90]. The quantitative application of this mechanism is hindered by a number of factors, but comparisons of semi-analytic derivations with experimental results show promise [8, 32, 90]. Uncertainties in application are rife and arise from a lack of knowledge and predictive capability, for example the distribution of wave/ligament sizes and relative velocities are rarely known. A main uncertainty is knowing when (i.e., at what disturbance height) and how much liquid is sheared from the film. Holowach et al. [32] suggest that the maximum amount of liquid loss occurs when the forces on the distorted wave tip are evenly balanced; Mayer [89] assumes waves break off

when the amplitude of the wave equals its wavelength; Woodmansee and Hanratty [69] observed that secondary waves separate from the main wave due to variations in air pressure induced by the flow over the waves. In reality, there is some probability that a protuberance will lose mass to shearing, one that increases with the amplitude of the disturbance and the relative velocity between the liquid projection and the gas. Also, there is some range of mass that can be sheared from the projection. An additional uncertainty in these formulations relates to wave shape, particularly wave crest shape, which affects the aerodynamic forces on the liquid. Azzopardi [33] reports experimental evidence that appears to be this type of atomization in annular flow. A very large percentage of the ligament is lost, however, so the liquid turbulence mechanism of the next paragraph can not be ruled out based on the limited amount of information available.

The experimental studies of Sarpkaya [39] dealing with atomization due to liquid turbulence found that some ligaments detach from the film at their base. They hypothesized that turbulent eddies at the base of these ligaments cause them to separate from the fluid. These studies and others, also in air-water systems, investigating turbulent-liquid flow showed that most ligaments breakup due to the Rayleigh mechanism, but that an estimated 10% undergo this turbulent separation [5, 39]. For different liquid-gas combinations this percentage may change. The droplets produced by this method are much larger than those created by the Rayleigh breakup mechanism because they contain the entire volume of the ligament.

Fragile shattering occurs when the liquid is unable to react (by deforming) to its surrounding flow because the speed of deformation exceeds the speed of liquid molecule relaxation [88]. Because the fluid is unable to relax quickly enough it acts, essentially, as a solid. Khavkin's [88] theoretical examination of secondary droplet breakup concerned flow in pressure swirl atomizers where the droplets were subjected to uneven force loading due to the centripetal forces, which acted to deform the droplets. If the viscosity of the liquid is sufficiently large it delays this relaxation; consequently, the liquid reacts like a solid and shatters. Ligaments subjected to swirl or other nonuniform velocity fields have the potential to undergo shattering. At this time, however, the existence of this mechanism remains speculation.

<u>Perforation Evolution</u>

In films the growth of perforations changes the topology of the liquid; however, the literature reports only attached "droplets" from perforations [79, 85]. Holes in sheets rapidly grow larger due to surface tension forces; holes in films may grow, shrink or stabilize [82, 84]. Only stable or expanding holes are of interest here. A thick rim is formed around an expanding hole [20, 84]. Air-borne droplets may be created from the collision of two or more rims. Possibly, the small growth rate of film holes results in collisions with insufficient force to generate droplets. There is the possibility that multiple perforations could create a network of thick ribbons which would alter the flow of and over the film. The generation of the large number of holes needed for this result is not expected in most atomization processes; at least not until the film becomes quite thin. Holes in flowing films take on parabolic-like shapes with thickened rims [81, 91]. The rim surface is curved above the surface of the bulk film. The gas flow will, consequently, be over a curved surface. This accelerated flow may separate part of the liquid from the wall or the rim. This separation may result in bag breakup if a thin liquid sheet remains attached to the wall or Rayleigh breakup of a separated ligament.

C. Prompt Atomization Mechanisms

The mechanisms considered here are those that produce immediate disintegration upon the liquid's exit from a nozzle. This regime might occur in a film configuration where the liquid was initially contained between two walls. Reitz and Bracco [12], who extensively studied prompt atomization in jets, note the possibility that there is still some (undetectably small) intact length of the jet and atomization, therefore, is not truly instantaneous. This assertion helps explain some of their results but remains to be verified. Jet breakup in this regime has been variously attributed to cavitation, liquid turbulence, velocity profile relaxation, acceleration in the boundary layers and aerodynamic effects, although experimental findings concluded that no single mechanism could explain the entire regime [12]. Less work seems to exist on the atomization regime of sheets. A few potential additional, sheet-related mechanisms can be gathered from the literature. For example, at the extreme end of the Perforation regime the splitting of the downstream edge of the sheet into ligaments has been observed [27]; as the relative velocity increases the intact sheet length decreases to the point that ligaments form very near the exit. The ligaments may break at very short lengths so that the breakup appears instantaneous.

Velocity profile relaxation causes atomization due to the perpendicular velocities already present in the liquid or caused by its change from confinement to free. This relaxation is likely to be less disruptive in a film arrangement due to the existence of only one free surface. Boundary layer relaxation/acceleration causes disintegration due to the changes in tangential stress at the interface and instabilities associated with the sudden change in boundary conditions. Studies have suggested that this relaxation may affect instabilities on the

surface of a jet or a film [92, 93], so this effect could clearly be important if there is any intact film. Without any intact length, boundary layer changes, like velocity profile relaxation, are less likely to be catastrophic in films than in sheets. Cavitation, liquid turbulence and aerodynamics effects are also known to have an effect on intact lengths of jets or sheets. Aerodynamic effects lead to the sheet shortening discussed in the previous paragraph; there is the possibility of a short intact length of fluid, much shorter than the diameter of the liquid, that is difficult to observe but upon which instabilities have the time/distance to grow and cause atomization. Cavitation causes pressure disruptions that help to disintegrate the liquid. Turbulent flow contains a radial component which may cause atomization. Again, in Reitz and Bracco's [12] study of jet atomization, no single one of these were found to be the cause of all prompt atomization behavior, but cavitation and aerodynamic effects help to explain a large part of jet behavior.

Recent studies [8, 65] observed a large amount of atomization occurring within a gas-centered coaxial-swirl atomizer, in a location where the fluid is a film. This internal breakup mode means there is little or no intact sheet at the exit, so that atomization appears, in some ways, to be prompt. However, this breakup occurs only if the liquid and gas are in contact prior to exiting the nozzle, so that atomization is not actually prompt but rather takes place in a film geometry instead of a sheet one. Unfortunately, due to the difficulty in studying this Prompt Atomization regime the preceding list is likely not exhaustive but a sampling of the commonly discussed possibilities.

D. Film Seperation

A final mechanism, which is unique to films, is separation around a corner. As a film flows (or tries to flow) around a corner there is an adverse acceleration relative to the density stratification. This acceleration can cause the film to separate from the wall. When this happens atomization can occur through two mechanisms. Either the separation causes a ligament to form, similar to the Sheet Pinching mechanism, or the film becomes a sheet and breaks up from a sheet geometry. Maroteaux et al. [94] looked at the possibility that the adverse pressure gradient causes Rayleigh-Taylor instabilities at the corner and postulated sheet pinching breakup at the corner if instabilities are above an empirical value. If this pinching does not occur, the film may separate from the wall but remain intact for a short distance. In this case the liquid will behave as a sheet during the atomization processes

IV. Conclusions

Atomization is a complex process that occurs over a wide range of geometries and conditions. A review of current understanding of the mechanisms involved in film atomization has been given. As evidenced above there are many possible drivers and paths leading to the atomization of a film. Clearly, different operating conditions may drastically alter the atomization mechanisms involved. Different mechanisms may be important in different situations, but the understanding of the mechanism itself is applicable over a wide range of conditions. Most injectors rely on the atomization of sheets or jets; consequently, little experimental and theoretical work has focused on film atomization. Film atomization is important in other processes, however, and various atomization mechanisms have been studied for these other systems.

The bulk of this paper focused on Surface Breakup processes, and atomization mechanisms have generally been divided into two subprocesses: disturbance formation and disturbance breakdown. Means of disturbance formation considered include liquid turbulence, hydrodynamic instabilities, gas-phase vortices, pressure fluctuations, droplet impingement and bubble bursting. Breakdown mechanisms include wave breaking, “bag” breakup, Rayleigh breakup, aerodynamic stripping, detachment of the disturbance at its base and fragile shattering. The causes and growth of perforations and possible prompt atomization mechanisms are also considered, although neither of these breakup modes is considered as likely in films as in sheets and/or jets.

One must remember that the breakdown of a disturbance only occurs if and when that projection reaches a critical size and remains at that size (or greater) for a sufficient time for the breakdown process to progress past a critical point. Consequently, not all disturbed interfaces will undergo atomization, especially since the fluid spends a limited time within the atomizer. These limitations demonstrate the need to predict not only the physics of disturbance initiation, growth and breakup, but the time and distances involved via predictions of growth rates, decay rates and critical sizes of disturbances and the time for breakdown of the disturbances as well. A final complication is that, in general, more than one mechanism will be possible under the operating conditions. Multiple mechanisms may occur simultaneous and aid or hamper one another. Further investigations are needed to address this issue.

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